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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : A61N 5/06

A1

(11) International Publication Number: WO 90/12619

(43) International Publication Date: 1 November 1990 (01.11.90)

(21) International Application Number: PCT/US90/02190

(22) International Filing Date: 23 April 1990 (23.04.90)

(30) Priority data:
342,481 24 April 1989 (24.04.89) US

(71) Applicant: ABIOMED, INC. [US/US]; 33 Cherry Hill Drive, Danvers, MA 01923 (US).

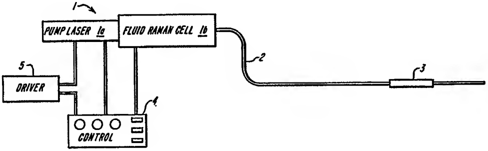
(72) Inventors: KUNG, Robert, T., V. ; 10 Lillian Terrace, Andover, MA 01810 (US). STEWART, Robert, B. ; 107 Brook Street, Haverhill, MA 01830 (US).

(74) Agents: FALKOFF, Michael, I. et al.; Lahive & Cockfield, 60 State Street, Boston, MA 02109 (US).

(81) Designated States: AT (European patent), BE (European + patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent), SU.

**Published**
*With international search report.*

(54) Title: LASER SURGERY SYSTEM




(57) Abstract

A multi-wavelength surgical laser apparatus (1) of improved construction employs a fluid-filled stimulated Raman scattering cell (1b, 20) in an optical feedback path of a pump laser (1a, 10) having a power in a range suitable for surgery, and drives the Raman cell at a high repetition rate in a manner to produce a laser output at a substantially shifted wavelength at a power commensurate with that of the pump laser. In a preferred system, the relative proportions of pump light and Raman scattered light are varied to achieve a desired cutting or coagulating action. Preferably, the pump laser is operated at a pulse repetition rate above five hundred Hz. The fluid Raman medium is pumped across the optical axis of the cell. The flow system effectively doubles the Raman conversion efficiency and permits high power output while lowering the Raman lasing threshold.

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# LASER SURGERY SYSTEM

## Background of the Invention

The present invention relates to surgical apparatus for the localized treatment of tissue by the application of light energy, and particularly to the area of laser surgery wherein tissue is cut, cauterized or otherwise subjected to laser light.

In such system there is a complicated set of design constraints imposed, on the one hand, by the available systems for generating laser light at particular wavelengths and powers suitable for different surgical applications, and, on the other hand, by the characteristics of probes or instruments for delivering the light to a surgical site and applying it to cut, coagulate or otherwise treat or analyze tissue.

In broad terms, the efficiency with which light of a given wavelength is absorbed by a particular tissue determines its depth of penetration, and thus the degree to which a pulse of such light will primarily cause either a superficial cutting action and tissue ablation without heat transfer to underlying tissue, or will cause a heating action to a depth effective to cauterize tissue. Both of these actions are generally desired for surgical purposes, thus requiring light of two substantially different wavelengths, at relatively high average power levels. In addition, light of

different wavelength at lower powers may also be desirable for visualization or certain forms of analysis, particularly in surgical arenas where the light is applied by endoscopic instrument.

The probes or instruments for delivering such light to a tissue site must guide the light with minimal losses from the laser source, and minimal parasitic heat generation. Two basic structures have evolved to achieve this purpose. In one, a highly reflective metallic tube structure, fabricated as an articulated arm, guides light by internal reflection to a probe end which is aimed at the tissue. In the other, fiber optics serve as the light guide, allowing greater flexibility in the delivery of light to, and manipulation of, the surgical probe. Hybrid delivery systems are also possible, although for particular wavelength bands absorption by the fiber may preclude the use of the fiber optic approach.

These constraints have meant, in practice, that a multi-wavelength surgical apparatus requires several distinct laser light sources, with precision alignment and coupling of the different sources into a common waveguide or probe structure, and the provision of a number of different controls to select working wavelength and set the desired power. These factors affect the production cost, the field reliability and the ease of use of such systems.

Summary of the Invention

Accordingly, it is an object of the present invention to provide a multi-wavelength surgical laser apparatus of improved construction.

This is accomplished according to a principal aspect of the invention by providing a fluid-filled stimulated Raman scattering cell in an optical feedback path of a pump laser having an output power in a range suitable for surgery, and driving the Raman cell in a manner to produce a laser output at a substantially shifted wavelength at a power commensurate with that of the pump laser. The relative proportion of pump and Raman scattered light are varied to achieve a desired cutting or coagulating action. In a preferred embodiment, the pump laser is operated at a pulse repetition rate between 200 and 3000 Hz, and means are provided to effect flow of the fluid medium across the optical axis of the Raman cell, effectively eliminating thermal lensing effects from the relaxation of stimulated molecules and achieving high Raman conversion efficiency. Lenses at the end of cell concentrate the pump laser output in a narrowed region of high intensity midway along the cell. With this driving arrangement the threshhold power to achieve Raman lasing is substantially lowered and a common Nd:YAG laser may drive the system with high efficiency at average power levels in the range of approximately one to thirty watts.

A prototype system includes a laser source with a hydrogen-filled Raman cell operated at 5-30

atmospheres, which was driven at a pulse rate of up to two kHz by a ten watt Nd:YAG laser at 1.06 microns, to produce an output at approximately 35 percent of the drive photons at 1.9 microns. Systems employing such a laser include a fiber for conducting output light to a surgical probe, and preferably include means for selectively varying the relative amounts of pump and Stokes radiation coupled into the fiber. Light generated at visible wavelengths by anti-Stokes processes in the Raman cell provides auxiliary beams for targeting or observation purposes.

## Brief Description of the Drawings

These and other features of the invention will be understood from the following disclosure, the teachings of which will be read in light of the background technology as understood by a person of ordinary skill in the art, and the illustrations of representative embodiments, wherein:

Figure 1 shows a surgical laser system according to the present invention;

Figure 2 shows the construction of a preferred embodiment of a surgical laser source according to the invention;

Figure 3 is a graph showing measured Stokes power as a function of pump laser pulse frequency for a static and a cross-flow Raman cell; and

Figure 4 shows the construction of a cross-flow Raman cell used in the embodiment of Figure 2.

Detailed Description of the Invention

A surgical system according to the invention has a laser source 1 including a pump laser 1a and a fluid Raman lasing cell 1b which operates to produce a relatively high average power laser beam at two or more substantially different wavelengths for surgery. Laser 1 is connected by a fiber light guide 2 to a surgical probe 3 which is illustrated schematically. Probe 3 may be a hand-held laser scalpel for external use, or may be a more complicated device for use in blood vessels or body passages or cavities, wherein the light from fiber 2 is guided to the tip of the probe, and the probe further contains various endoscopic, tip steering, beam forming or material removal or aspirating means or tissue analysis devices. The elements of a probe are considered conventional, and are not described further herein. A controller 4 selects the power, duration and wavelength of light supplied by source 1 to the probe, and a driver module 5 operates the pump laser in a manner to drive the Raman cell at a high average power level.

Figure 2 shows in more detail the construction employed in one prototype of the laser source. In this embodiment, pump laser 1a was a solid state Nd:YAG laser which although subject to power drop-off in the preferred driving arrangement described below was operated to produce an average power output of 4-6 watts at a wavelength of 1.06 microns. The Raman cell was a gaseous hydrogen Raman cell which was arranged in a direct feedback path with the pump laser, and was excited by pulsed 1.06

micron light from the pump laser to emit stimulated Raman scattered light at 1.9 microns. The driving and control system, discussed further below, pumped the cell to produce a light output at a power level comparable to that of the pump laser.

It has long been known that certain gaseous materials, such as deuterium, hydrogen, carbon dioxide and others can undergo stimulation of their internal energy modes by laser light to emit coherent light of a shifted frequency. A dual wavelength source consisting of a Raman cell driven by a pump laser source has previously been proposed as a way of producing a wavelength output shifted from that of a fixed source. Research has shown, however, that the peak power intensity threshhold required for a pump laser to initiate Raman lasing (SRS) emission even in a relatively active Raman scattering material such as hydrogen is in the tens or hundreds of thousands of kilowatts. The lowest threshholds have been demonstrated in special cases, e.g., for the principal $TEM_{00}$ mode using specialized wave guiding apparatus to achieve the greatest conversion efficiency. For multimode beams the threshholds are higher, and this has effectively ruled out the possibility of achieving a surgically useful level of output from a fluid Raman cell driven by any of the common solid state pump lasers, such as YAG lasers which operate at an average power level of under 100 watts.

Applicant has now overcome these limitations and achieved a sustained output from a gas-filled Raman cell at an average power level suitable for

surgery using an inexpensive and relatively small Nd:YAG laser of approximately fifteen watts average power. The fluid-filled Raman cell is made to achieve an effective power output by switching the pump laser at a high repetition rate and focusing light along a feedback path of the pump laser into an interaction region within the Raman cell while a flow of fluid is provided across the interaction region. The lasing threshhold is lowered while the Stokes efficiency is raised to a level such that a watt or more of Stokes power is readily generated with the low power pump laser. Such Raman efficiency has previously been possible with pump lasers having an output intensity one or two orders of magnitude higher.

In the prototype experimental arrangement shown in Figure 2, the pump laser 1a includes a Nd:YAG rod 10 six millimeters diameter by ten centimeters long which is pumped by a single Krypton flashlamp (not shown). An acousto-optic Q-switch 12 is controlled by the driver 5 (Figure 1) to pulse the laser at repetition rates of up to several kilohertz. The Raman cell 20 is placed in a direct feedback path of the pump laser by an optical design shown as an intracavity three mirror dual laser cavity configuration.

Two mirrors, $M_1$ and $M_3$, form an oscillator cavity for the Nd:YAG pump radiation. These mirrors have a high reflectivity ($R_p > 99.9\%$) dielectric coating at the 1.06 micron pump wavelength. A third, intermediate mirror $M_2$ is placed such that mirrors $M_2$ and $M_3$ confine the Stokes radiation at 1.9 microns of

the Raman cell 20. Windows 21a, 21b close the cell. The windows are transmissive at all relevant wavelengths, and serve to contain the high pressure Raman fluid medium. The intracavity mirror, $M_2$, is coated for high transmittance at 1.06 microns ($R_p$ < 0.5%) and high reflectivity at 1.9 microns ($R_s$ > 99%). Mirror $M_3$ is used to output couple the Stokes radiation, and in different embodiments its reflectivity at 1.9 microns is varied, with different optical coatings, to achieve a desired percentage transmittance of that wavelength. Two identical intracavity lenses 14, 16 are placed at the ends of the Raman cell 20, and serve to focus the light in the cavity into a relatively small region at the center of the cell. The intracavity lenses have a focal length of ten centimeters, an f-number of approximately f10-f30, and are placed in a nearly concentric configuration, thus focusing all radiation passing between the mirrors $M_2$ and $M_3$ into a small (under approximately one centimeter long) segment at the center of the Raman cell. Both the intracavity lenses 14, 16 and Raman cell windows 21a, 21b are antireflection coated to achieve less than 0.25% reflectivity per surface at both 1.06 and 1.9 microns wavelengths. Finally, a closed loop flowing gas system circulates hydrogen at 5-20 atmospheres through the cell 20 across the optical axis at linear flow velocities of about 200 cm/sec. The total cavity length is about one meter.

Using the above laser source configuration, the energy per 150 ns pulse of the Nd:YAG laser at a repetition frequency of 1 kHz was determined and the Raman cell was then filled with hydrogen. Using a

Molectron P5-01 fast pyroelectric detector and a Tektronix 7904 500 Mhz oscilloscope, the temporal pulse shapes of the pump and the Stokes radiation were recorded. The beam quality was evaluated for both the pump and the Stokes beams by measuring the spot size focused from the beam by an extracavity lens, and comparing it to the size of a theoretically calculated diffraction-limited beam of the same aperture. Finally, the average output Stokes power was measured as a function of repetition rate for both a static and a flowing fluid in the cell.

A detailed consideration of theoretical models as well as measurements on pump laser and stimulated Raman emissions was undertaken for the experimental system shown in Figure 2, with different mirrors $M_3$ substituted. The mirror $M_3$ was highly reflective at the pump wavelength, and was coated to provide a preselected reflectance $R_s$ at the Stokes wavelength between 3% and 90% (Rs = 10%, 64% or 97%). It thus served as a selected ratio output coupler for the Stokes wavelength beam. It will be understood that other arrangements can be provided in the light feedback loop to variably couple different proportions of the pump and the Raman beams out of the laser into the fiber 2 (Figure 1). For example, element $M_3$ may be a Fabry-Perot etalon which is continuously adjustable to vary the light of each wavelength coupled out of the laser cavity.

Using such a configuration to explore Stokes conversion efficiencies at a repetition rate of 100 Hz with a 150 ns pump pulse, applicant observed a

shorter, approximately 100 ns, Stokes pulse, with a peak conversion efficiency occurring when mirror $M_3$ coupled approximately 30-40% of the Stokes energy as the output. Elementary observations on pump and Stokes beam quality also revealed that the Raman cell was operating to clean up the laser beam, by forming a Stokes beam of better quality than the pump beam as many modes of the solid state laser excited the stokes $TEM_{00}$ mode. The result was a Stokes beam capable of better focusing, thus enhancing its usefulness for fiber optic applications, Measurements on the beams indicated that while the multimode pump laser beam had under approximately twenty percent of its power in the $TEM_{00}$ mode, the Stokes output beam had over ninety percent of its power in the $TEM_{00}$ mode. Further, the $TEM_{00}$ absolute power level in the Stokes beam exceeded that in the pump beam.

As the pulse repetition rate was increased the total average power increasingly departed from being linear in repetition rate. The dashed line in Figure 3 represents a computer-modeled calculation of Stokes output power with frequency, without any flow of gas through the Raman cell. The Raman-active central region of the cell is subject to extreme thermal gradients. The resulting variation of refractive index disrupts the focusing of light into the center of the cell and causes the significant drop in efficiency. The effects of this thermally-induced beam scattering or "thermal lensing" are modeled in the dashed-line graph. Figure 3 also shows the computer-modeled Stokes laser

power (solid line) in watts, as a function of the Q-switching rate. The power drop-off at Q-switching frequencies of the pump laser above 2000 Hz is primarily due to the .25 millisecond fluorescence lifetime of the Nd:YAG crystal at the 1.06 micron pump frequency, and the consequent lowering of inversion population at higher frequencies.

The experimental data points indicated by crosses were measured for a Raman cell filled with a stationary medium, and they closely fit the modeled Raman drop-off data, rising only to about one and a half watts at two kilohertz. Finally, the experimental data points indicated by square boxes were measured when a flow of the Raman fluid through the cell was maintained to remove from the optical path a portion of that fluid which had been excited by the previous pump pulse. The Stokes output remained linear well above the modest 300 Hz rate at which the stationary fluid cell degraded. While a drop in per-pulse efficiency above one kHz was noted, as compared with the computed curve (solid line) this is attributed to the limited flow rate achieved by the experimental flow mechanism, as described below.

Figure 4 shows the overall construction of the cross-flow Raman cell 20 used in the above experiments. The cell 20 was filled with gaseous hydrogen maintained at a pressure between ten and twenty atmospheres, and was part of a closed fluid circulation system 40 having as basic element a reservoir/fan housing 50, the Raman cell 20, and connecting conduits 42 all connected in a fluid flow loop.

Reservoir/fan housing 50 is formed of two fluid-sealable separable half drums 51a, 51b, with an electrical feed-through 52 for an electric circulating fan (not shown) located in half drum 51a. Preferably vanes or baffles are provided in the flow path through the reservoir to enhance contact of the circulating gas with the housing and promote thermal conduction from the gas. In this aspect, the housing serves to dissipate heat from the circulating gas to the external environment.

The body of the Raman cell 20 is formed as a cross of 2.5 centimeter OD stainless steel conduit, with an axially oriented tubular member 30 having its ends closed by windows 21a, 21b constituting the lasing cell as shown in Figure 2, and transversely oriented conduit branches 32a, 32b joined at the center of the cell. The conduits 42 are welded to the cross conduits at 43, closing the circulation loop, and a slidable o-ring seal structure is provided at the junction of a conduit 42 with housing 51b to allow disassembly of the housing. Various flange couplings, seals and packing arrangements may be used at any of the junctions, and are not specifically illustrated. One or more valved filler ports may be provided, preferably in the housing 50, for evacuating and filling the system. The fluid circulating fan is selected to provide a flow rate of approximately 500 cc/sec., thus providing a gas cross-flow at a speed in excess of 150 cm./sec at the focal region in the center of cell 20.

Applicant found that when the above described system was operated at a fluid pressure of approximately ten atmospheres, the system produced a significant amount of CARS radiation at .737 and .534 microns, suitable for laser targeting and tissue observation.

In the prototype system, the focal region of the cell provided an interaction region of approximately one millimeter diameter or less in which active Raman laser processes occurred. The above flow rates were effective to fully replace the medium directly in the excitation path at pump laser repetition rates up to about one kiloherz, but as the repetition rate was raised beyond that frequency, the thermal diffusion rate of the gaseous hydrogen allowed an increasingly significant amount of gas to reside in the interaction area. This previously-stimulated gas, which was not in its ground vibrational state, accounted for the drop-off from linearity in measured energy noted in Figure 3. In further embodiments, the cross flow circulation system is preferably of a capacity to provide a cross-flow of gas between pulses which is greater than the interaction width by an amount greater than the characteristic interpulse thermal diffusion distance of the gaseous medium. For the above described optical configuration and cell dimensions, a cross-flow velocity of 500-1000 cm./sec. should be adequate for repetition rates up to three kiloherz.

As described above, the invention achieves a substantially shifted wavelength from that of a solid state pump laser in a fluid Raman scattering cell at a power commensurate with that of the pump laser. The substantially lowered Raman lasing threshhold allows for the first time the practical application of large Raman shifts to a class of low power solid state lasers, and the provision of surgically effective power levels into fiber-compatible delivery systems.

While the output coupling of the two laser colors into the fiber has been described in terms of the use of partially reflective mirrors, other output coupling schemes, including polarization control, and filtering of the output light, may be employed in the described laser source to vary the light of each wavelength which is coupled into the fiber 2. One such means is the substitution for mirror $M_3$ of a piezo-electrically controlled interference filter, such as a Fabry-Perot interferometer, as an output coupler with variable reflectivity at the pump wavelength. Such variable reflectivity is achievable by varying the gap between two optical flats each having proper reflectivity coatings at the pump wavelength. The reflectivity for the Stokes wavelength is maintained at an optimal value. By varying the gap of the Fabry-Perot interferometer, the output is then made to vary from mostly Stokes to mostly pump outputs. With high output coupling at the pump wavelength, no Stokes beam will be generated, while low output coupling at the pump wavelength will yield mostly Stokes output.

It will be understood that while the prototype embodiment was implemented with a Nd:YAG pump laser and gaseous hydrogen Raman cell to produce laser power at 1.06 microns and 1.9 microns adapted to fiber optic transmission and wavelengths having different surgical properties, other pump and Raman lasers are contemplated to achieve different operative wavelengths in systems according to the invention. In other embodiments, the teachings of the invention may be advantageously applied to other Raman-active media, including $D_2$, $N_2O$, $CO_2$, $SF_6$, NO, CO, HBr, $N_2$ and others.

The invention being thus disclosed and described in connection with the illustrated embodiments, variations and modifications thereof will occur to those skilled in the art, and are intended to be included within the scope of the invention, as defined by the claims appended hereto.

What is claimed is:

Claims:

1. A laser surgical apparatus comprising

a solid state pump laser located in a laser cavity defined by reflective end mirrors

an intracavity gas-filled Raman cell located in an optical focusing feedback path of said solid state pump laser for generating in a focal region of said path a stimulated Raman scattered laser beam of frequency offset from that of the pump laser

an optical fiber guide for guiding light to a surgical probe

output coupling means for selectively coupling laser light from said cavity into the optical fiber guide in differing relative proportions of pump laser light and Raman laser light, and

a surgical probe which receives light from the optical fiber guide and applies light therefrom to tissue, said pump laser and said Raman cell each producing light of differing tissue absorption properties so that said output coupling means is operative to selectively adjust the relative ablative and coagulative properties of the light applied by the probe, and

means for providing a cross flow of gas in said Raman cell effective to overcome thermal lensing in said focal region.

2. A laser surgical apparatus according to claim 1, further comprising drive means for driving said Raman cell with said pump laser at a high pulse repetition rate while controlling fluid environment to maintain a substantially uniform Raman conversion efficiency.

3. A laser surgical apparatus according to claim 2, wherein said pump laser is a Nd:YAG laser and said Raman cell is filled with hydrogen.

4. A laser surgical apparatus according to claim 3, wherein said Raman cell is operated at a pressure of approximately ten atmospheres.

5. A laser source for a surgical probe, such laser source comprising

a solid state pump laser having a first characteristic lasing frequency $f_0$, said pump laser being located in a cavity defined by reflective end mirror surfaces

a Raman cell containing a Raman scattering fluid medium and located within an optical feedback path of said pump laser within said cavity, said Raman cell being characterized by stimulated Raman scattering at a second characteristic frequency $f_1$ offset from $f_0$

focusing means for tightly focusing light from said pump laser within a central focal region of said Raman cell

cross flow means for providing a flow of said Raman scattering medium across said central focal region at a rate effective to overcome thermal lensing effects as said pump laser is operated, and

output means for selectively coupling varying amounts of laser light of frequency $f_1$ and $f_0$ from said cavity to a fiber to guide the laser light to a surgical implement,

said cross flow means being effective to permit sustained stimulated Raman scattering in said cell upon repetitive excitation pulsing by said pump laser at an average power greater than one watt.

6. A laser source for generating a laser output beam, such source comprising

a laser cavity defined by reflective end surfaces

a pump laser operated to produce laser pulses at frequency $f_0$ and with an average power above several watts

a gas-filled Raman cell located in said cavity in an optical path of said pump laser and having a characteristic stimulated Raman scattering frequency $f_1$ substantially different from $f_0$, and

means for driving said Raman cell with said pump laser to produce an output beam of frequency $f_1$ at a power level over approximately twenty-five percent of the pump laser average power level, said means for driving including

i) focusing means for tightly focusing the pump laser light into a focal region within said Raman cell effective to induce Stokes emission at said frequency $f_1$, and

ii) cross flow means for providing a cross flow of gas in said focal region effective to overcome thermal lensing.

7. A laser source according to claim 6, wherein the means for driving includes means for applying pump laser pulses into a region of said Raman cell at a pulse repetition rate over 300 sec.$^{-1}$ while

providing a cross flow within the cell at a rate sufficient to maintain Raman scattering efficiency in the central region.

8. A laser source according to claim 7, further including means for focusing light to a level effective to maintain a stimulated Raman laser scattering process within said central region of the cell.

9. A laser source according to claim 6, further including means for providing a flow of Raman stimulatable medium across the axis of said cell at a rate effective to prevent thermal lensing effects.

10. A laser source according to claim 9, wherein the flow is provided at a rate such that between consecutive pulses of the pump laser the Raman medium in the central region is displaced further than the diameter of the central region plus a characteristic diffusion distance of the Raman medium.

11. A laser source according to claim 6, further including output control means for varying the amounts of $f_0$ and $f_1$ light coupled as an output from the cavity.

12. A laser source according to claim 7, wherein the means for applying pump laser pulses applies pulses having a duration which is long compared to the transit time of the Raman cell.

13. A laser source according to 7, wherein said pump laser is a Q-switched YAG laser.

14. A laser source according to claim 13, wherein said Raman cell is a hydrogen-filled Raman cell operated to produce a visible coherent anti-Stokes Raman scattering (CARS) beam for targeting or observation of a surgical probe.

15. A surgical laser source comprising

i) a solid state pump laser emitting light at a first characteristic lasing wavelength $\lambda_0$

ii) a Raman cell having a Raman scattering medium with characteristic stimulated Raman scattering at a second wavelength $\lambda_1$ substantially shifted from $\lambda_0$

iii) means for providing a flow of said medium across a focal region of an optical path through said Raman cell at a rate effective to overcome thermal lensing in said focal region,

iv) means for driving said Raman cell with said pump laser along the optical path to stimulate emission of light at wavelength $\lambda_1$ in said focal region at a repetition rate effective to provide a power level corresponding to the power level of the pump laser, and

v) means for coupling light of at least one of the wavelengths $\lambda_0$ and $\lambda_1$ from the source into a fiber for connection to a laser surgical probe, said means for coupling being operative to select the amount of light coupled into the fiber, and each said wavelength having a different tissue absorption or penetration

characteristic such that the relative cutting and coagulating properties of said probe are varied by said means for coupling.

16. A surgical laser source according to claim 15, wherein both of said wavelengths $\lambda_0$ and $\lambda_1$ are transmitted by an optical fiber waveguide, and further comprising an optical fiber waveguide coupled to said means for coupling.

17. A method of providing a surgical laser, such method comprising the steps of

providing a solid state pump laser having an average power level of at least several watts at a first wavelength $\lambda_0$,

focusing a feedback path of said pump laser into a focal region within an intracavity fluid Raman cell having a Raman scattering wavelength $\lambda_1$ substantially shifted from $\lambda_0$

driving said pump laser in a pulsed mode to achieve Raman laser emission from said cell at wavelength $\lambda_1$ while providing a cross flow of fluid in said focal region effective to overcome thermal lensing and achieve a Raman laser power which is a substantially linear function of pump pulse rate, wherein said step of driving includes driving at a sufficiently high pulse repetition rate to achieve a $\lambda_1$ power level suitable for surgery, and

coupling a selected proportion of laser light from said feedback path into a fiber waveguide for delivery to a surgical probe.

18. The method of claim 17, wherein the step of coupling includes coupling different non-zero proportions of light of wavelength $\lambda_0$ and of wavelength $\lambda_1$.

19. A surgical laser system comprising

a pump laser with a laser output at a first wavelength $\lambda_0$ and a pulse rate of $p > 100$ pulses per second,

a fluid-filled Raman cell arranged in a focused optical feedback path with said pump laser to produce light at a different wavelength $\lambda_1$ in a focal region within said Raman cell,

means for recirculating a Raman fluid medium through said Raman cell across said focal region at a speed greater than the heat diffusion length of said fluid medium multiplied by p,

means for driving said pump laser at a power effective to surgically treat body tissue, and

means for coupling a desired proportion of light from said pump laser and said Raman cell into an optical waveguide for surgical application to body tissue.

20. A laser source comprising

a solid state pump laser providing a pulsed multimode beam at a first wavelength $\lambda_0$ having the $TEM_{00}$ mode as a minor component

a fluid filled Raman cell arranged in a focused optical feedback path with said pump laser to produce a Stokes beam at a shifted wavelength $\lambda_1$ in a focal region within said Raman cell,

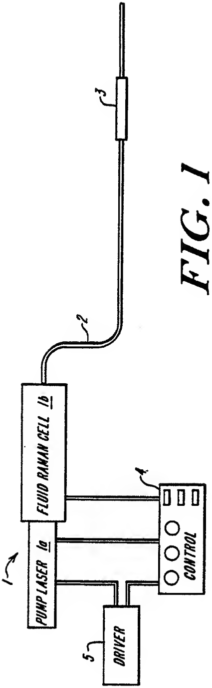
means for overcoming thermal lensing in said focal region such that the Stokes beam power is a substantially linear function of pulse rate of said pump laser and the Stokes beam has the $TEM_{00}$ mode as a substantial component, and

means for coupling the Stokes beam to an output thereby providing a beam of improved quality suitable for fiber optic delivery as an output beam.

21. A laser source according to claim 20, further comprising an optical fiber waveguide, and wherein said means for coupling couples the output beam into said waveguide.

22. A laser source according to claim 20, wherein said pump laser is a Nd laser and said Raman cell is a hydrogen cell, producing $\lambda_0$ and $\lambda_1$ of 1.06 microns and 1.9 microns, respectively.

23. A laser source according to claim 20, wherein the output beam has greater absolute power in the $TEM_{00}$ mode than has the pump laser.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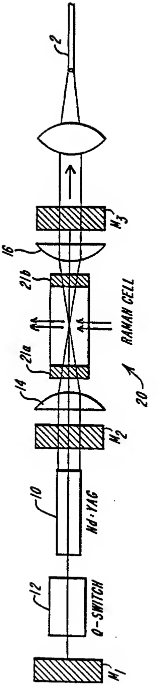
FLUID RAMAN CELL 1b
CONTROL
DRIVER
1
2
3
4
5

FIG. 1


Q-SWITCH
Nd:YAG
RAMAN CELL
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$M_2$
$M_3$
10
12
14
16
21a
21b
20
2

FIG. 2

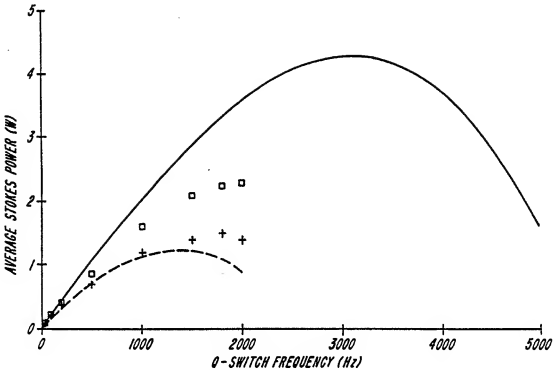
AVERAGE STOKES POWER (W)
0
1
2
3
4
5
0
1000
2000
3000
4000
5000
Q-SWITCH FREQUENCY (Hz)

FIG. 3

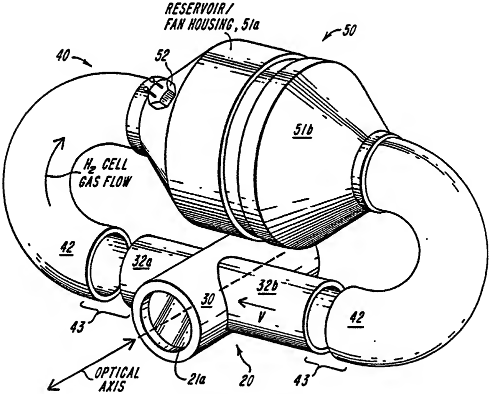
RESERVOIR/
FAN HOUSING, 51a
50
40
52
51b
$H_2$ CELL
GAS FLOW
42
32a
32b
30
V
42
43
OPTICAL
AXIS
21a
20
43

FIG. 4

# INTERNATIONAL SEARCH REPORT

International Application No PCT/US90/02190

**I. CLASSIFICATION OF SUBJECT MATTER** (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(5): A61N 5/06
US CL.: 606/2

**II. FIELDS SEARCHED**

Minimum Documentation Searched [4]

| Classification System | Classification Symbols |
|---|---|
| U.S. | 606/2-18; 128/395, 397, 398; 372/3, 9, 25, 29, 53, 54; 307/426 |

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

**III. DOCUMENTS CONSIDERED TO BE RELEVANT** [14]

| Category * | Citation of Document, [16] with indication, where appropriate, of the relevant passages [17] | Relevant to Claim No. [18] |
|---|---|---|
| X<br>Y | US,A, 4,327,337 (LIU) 27 April 1982<br>See the entire document | 6-11<br>1-5,7-10,12-20,23 |
| Y | US,A, 4,178,565 (MORTON) 11 December 1979<br>See the entire document | 2-5,7-10,12-15,<br>18-20 |
| Y | US,A, 4,144,464 (LOREE) 13 March 1979<br>See the entire document | 1-5, 8, 15-20 |
| Y | US,A, 3,705,992 (IPPEN) 12 December 1972<br>See the entire document | 1-5, 16, 17,19 |
| Y | US,A, 4,336,809 (CLARK) 29 June 1982<br>See the entire document | 1-4, 16-20 |
| Y | US,A, 3,793,541 (ASHKIN) 19 February 1974<br>See the entire document | 21 - 23 |
| Y,P | US,A, 4,829,262 (HIRUMA) 09 May 1989<br>See the entire document | 21 - 23 |

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

**IV. CERTIFICATION**

| Date of the Actual Completion of the International Search [2] | Date of Mailing of this International Search Report [2] |
|---|---|
| 31 May 1990 | 16 JUL 1990 |
| **International Searching Authority** [1] | **Signature of Authorized Officer** [20] |
| ISA/US | David Shay |